AD-A285 066

David Sarnoff Research Center

Subsidiary of SRI International

CERAMIC/METAL COMPOSITE CIRCUIT-BOARD-LEVEL TECHNOLOGY FOR APPLICATION SPECIFIC ELECTRONIC MODULES (ASEMs)

Contract No.: DAAB07-94-C-C009

TECHNICAL REPORT

PERIOD: June 24, 1994 Through September 21, 1994

Sponsored by:
- Advanced Research Projects Agency
- Electronic Systems Tech. Office
- Application Specific Electronics Module Program
- ARPA Order No. A840
- Issued by U.S. Army CECOM under contract No. DAAB07-94-C-C009

Prepared for: COMMANDER, USACECOM
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Prepared By — September 21, 1994

Approved By — September 21, 1994

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Summary

Most of the major elements of the LTCC-M technology have been developed, and all have been shown to be compatible. The development of the green tape ceramic has been completed. The materials and processing have been developed to fire this green tape to a Cu/Mo/Cu metal core such that a very dense ceramic is formed with "zero" lateral (x-y plane) shrinkage. Thick film conductors have been developed for use with this tape. The process for mass fabrication of electrical feedthroughs in the Cu/Mo/Cu core has been successfully extended to laser drilled holes as small as 7 mils in diameter. Additionally, thin film overlays with a photosensitive BCB (from Dow Chemical) dielectric have been deposited on top of the fired ceramic.

Section I
WBS Task 1.1: Metal Core Fabrication

A. TASK OBJECTIVE

The metal core fabrication serves 2 distinct purposes in the manufacture of double sided low temperature cofired ceramic on metal (LTCC-M) substrates. These are: (1) to provide a high density of electrical interconnections between the top and bottom sides of the substrate, and (2) to restrain the shrinkage of the ceramic during firing, so that **"zero" lateral shrinkage** is achieved Within this task are 2 entirely separate developments; namely (1) the development of materials and processes to fabricate many small electrical feedthroughs within the metal core and (2) the development of materials and processes to fire the ceramic onto the metal core with "zero" x-y shrinkage.

B. INTRODUCTION

In last technical report the feedthrough fabrication process was described and verified with machine drilled holes (0.013" diameter). The basic feedthrough fabrication process involves opening up a hole (e.g. drilling and deburring), applying a layer of nickel to seal the molybdenum, depositing an annular ring of insulation, and finally depositing a conductor in the center core of the insulator. The insulation and center conductors are deposited by modified screen printing techniques, using standard equipment. During this past quarter this process has been extended to laser drilled holes as small as 7 mils in diameter. Laser drilling has been identified as the fastest and most cost-effective method for drilling a large number of small holes in a metal core. The data and conclusions related to laser drilled holes will be included in this report.

This past quarter emphasis was placed on developing the materials and processes required to fired the green tape to the Cu/Mo/Cu core without any lateral (x-y) shrinkage occurring during firing. These materials and processes will be reported.

C. HOLE FABRICATION

Experiments were performed using a laser to drill holes in Cu/Mo/Cu metal cores. Holes were drilled by Coherent General (Sturbridge, MA) using a Nd:YAG laser at 15-30 watts, with 0.6 msec. pulse lengths. 13 mil diameter holes could be readily drilled in both 20 and 40 mil thick Cu/Mo/Cu. The minimum hole diameter was 7 mils for 20 mil thick Cu/Mo/Cu and 8 mils for 40 mil Cu/Mo/Cu. After drilling a "slag" residue remained around the perimeter of the laser drilled holes, this could be removed by mechanical means.

Next quarter work will also continue to optimize the laser drilling process so that "slag" residue is minimized or eliminated.

D. ELECTRICAL FEEDTHROUGH FABRICATION RESULTS

The cross section of an electrical feedthrough fabricated from a laser drilled 7 mil diameter hole is shown in Figure I.1. The processing developed for machine drilled holes carried over to laser drilled holes. The suction screen printing technique delivered sufficient insulation to cover all irregularities of the laser drilling process. The center conductors could be readily filled for the 7 mil diameter feedthroughs (20 mil thick metal core) by double pass stencil (2 mil thick, etched stainless steel) printing.

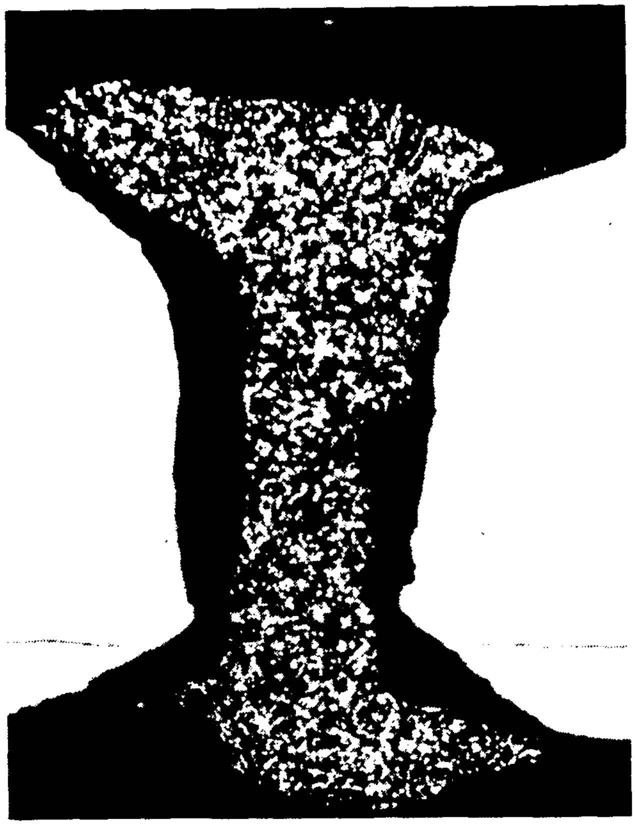


Figure I.1: Cross section through an electrical feedthrough fabricated from a 7 mil diameter laser drilled hole in 20 mil thick Cu/Mo/Cu.

E. SHRINKAGE CONTROL

The key property of the LTCC-M process that sets it apart from all other cofired ceramic technologies is the simple method used to restrain the ceramic from shrinking in the lateral plane, while obtaining a fully sintered ceramic. This is accomplished by the use of a custom glass bonding layer that attaches the ceramic to the metal core during the ceramic firing process. Additionally, the ceramic has good adhesion to metal core. The development of a the bonding layer seems to be quite specific to the green tape formulation.

Prior to deposition of the bonding layer onto the metal core, the Cu/Mo/Cu substrate requires surface preparation to:

- Prevent oxidation of the Mo during air firing steps that can be in excess of 900°C
- Promote adhesion to the ceramic

The process shown in Figure I.2 was developed and successfully used to make LTCC-M substrates having a Cu/Mo/Cu core.

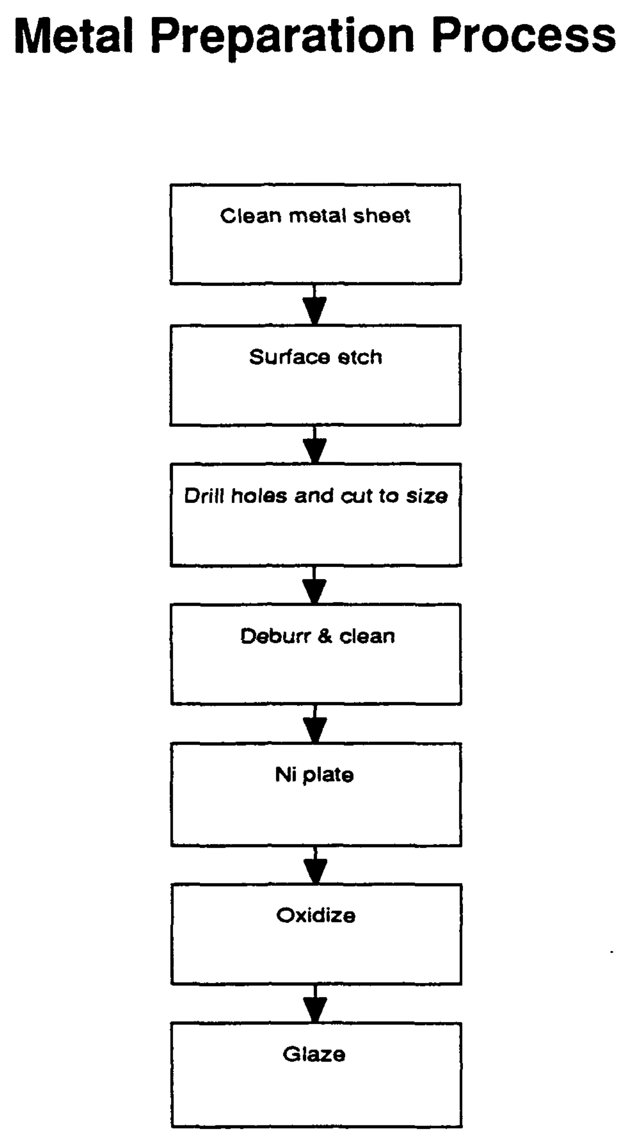


Figure I.2: The Cu/Mo/Cu preparation for 2-sided LTCC-M processing.

After the Cu/Mo/Cu was prepared, the bonding layer could be applied by formulating a thick film ink containing the bonding glass. A custom glass designated M-31 was chosen as principal bonding glass material for use this past quarter. After the M-31 glazing ink is printed, it can reflowed onto the metal core by firing in air at about 750 - 800°C peak temperature. Figure I.3 shows a Differential Thermal Analysis (DTA) plot for this material.

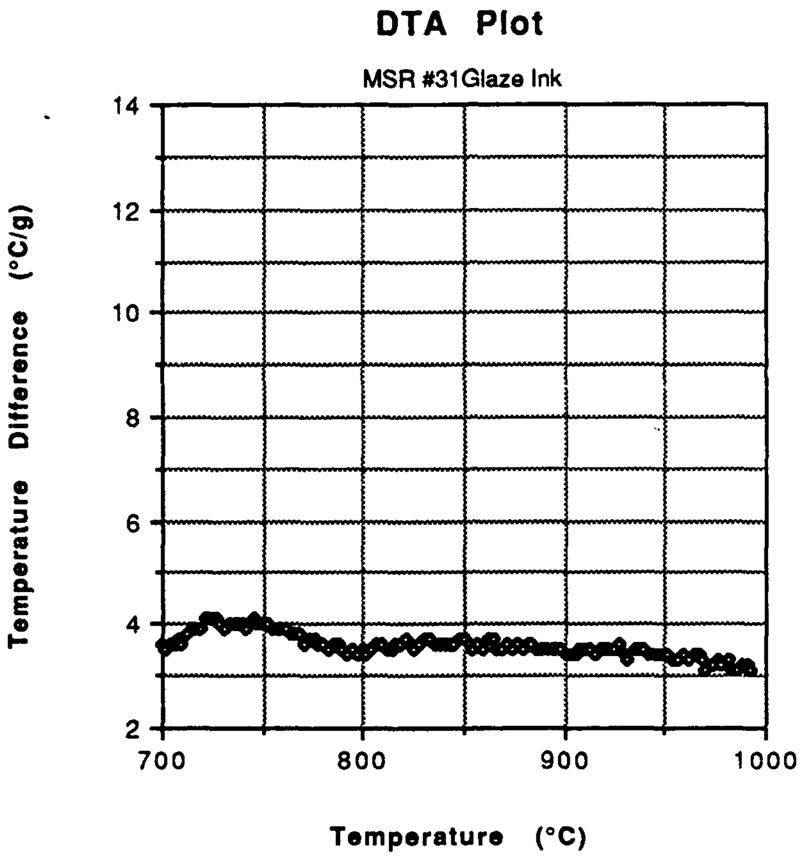


Figure I.3: DTA plot for the bonding glaze.

When the ABT-24 green tape (described in section II) is then laminated to the Cu/Mo/Cu core and fired, no shrinkage was measured relative to features measured after lamination. In both cases (before and after firing) a net expansion averaging 0.15% was measured. The expansion occurring during uniaxial lamination is a function the organic component of the green tape, as well as the lamination pressure, temperature, and time.

F. PLAN FOR NEXT QUARTER

- Laser drilling holes in Cu/Mo/Cu will continue with the aim of eliminating the "slag" residue that is formed
- Shrinkage control experiments will continue on larger area parts

Section II
WBS Task 1.2: LTCC Ceramic Development

A. TASK OBJECTIVE

The development of glass-ceramic dielectric compositions suitable for the fabrication of LTCC-M on Cu/Mo/Cu cores and having high density, thick film silver wiring.

B. INTRODUCTION

In the previous report, the development and characterization of three potentially useful glass-ceramic compositions for the ASEM application had been described. This work had also led to the selection of a composition designated as KU-4 as the prime candidate for the ASEM project. Since then, the KU-4 dielectric has been successfully cofired on Cu/Mo/Cu cores with zero x-y shrinkage while attaining near theoretical density. Also, the KU-4 dielectric was found to have very low dielectric loss values well into GHz frequency range, as reported previously. This was verified by measuring the insertion loss on a thin film strip line on a polished surface of sintered KU-4. As shown in Figure II.1 these losses tracked the insertion losses measured on polished alumina substrates to 40GHz. However, the dielectric composition was found to need further modification, first to make it perfectly flat-firing on Cu/Mo/Cu, and second to lower the peak firing temperature to below 900°C for better compatibility with silver thick film firing profiles.

Microstrip 50Ω Transmission Line using Low Temperature Cofired Ceramic / Metal Materials Technology

- ***Polished Surface Finish***
- ***Ti | Cu | Ni | Au Thin Film Conductors***

• *Potential Technology for Low Cost / High Volume RF/Microwave Circuits* •

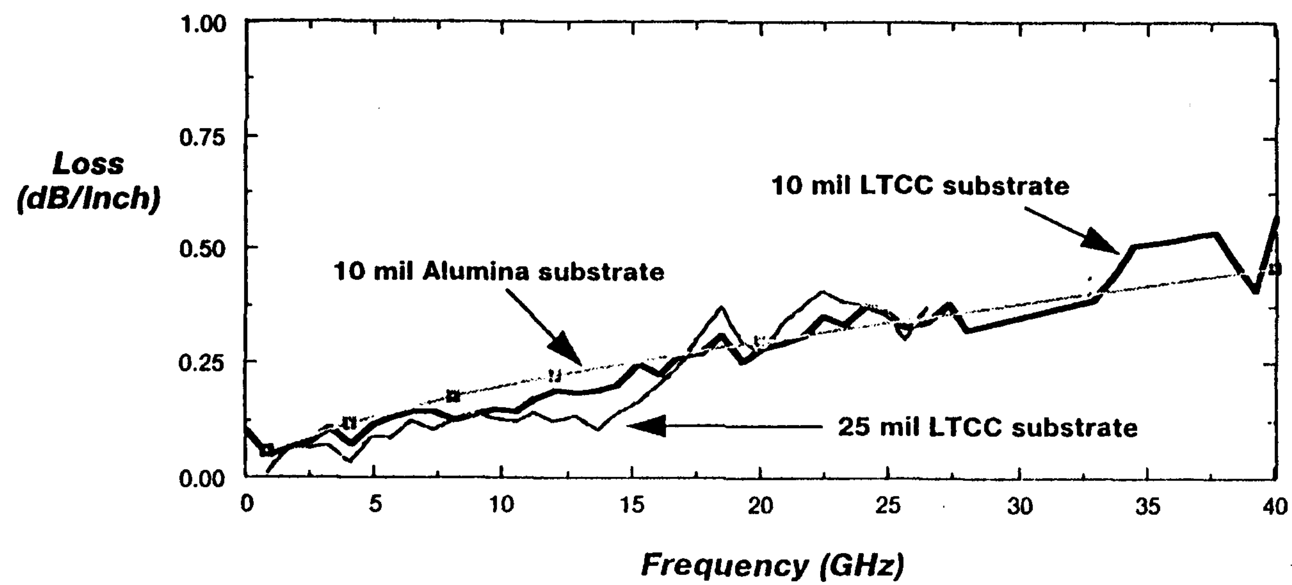


Figure II.2

C: MODIFICATION OF KU-4 GLASS-CERAMIC

Nearly 30 batches of KU-4 glass have been prepared to date and have been characterized by DTA and other means. It has been found that these 30 batches had reproducible sintering and crystallization behavior, with densification beginning at about 870°C and complete crystallization requiring at least about 925°C. The best dielectric properties viz. low k and low loss characteristics were reproducibly obtained in the fully crystallized state. In numerous experiments involving the cofiring of the KU-4 tape on Cu/Mo/Cu cores, it was found that, in the fully crystallized condition (i.e. when the peak sintering temperature was 925°C), the thermal expansion of the dielectric was somewhat lower than that of the Cu/Mo/Cu cores, which resulted in a slight convex camber towards the dielectric. On the other hand, if the peak temperature did not exceed 900°C, the camber would be concave towards the dielectric indicating a higher TCE for the dielectric than the core. Many attempts made to obtain flat substrates by firing at a peak temperatures of 900°C and 925°C were unsuccessful.

Since the TCE adjustment needed for KU-4 to be compatible with Cu/Mo/Cu was judged to be a small one, it was decided to modify the TCE by mixing KU-4 with a suitable additive having a higher TCE. At first several crystalline ceramic additives such as alumina, forsterite and quartz, were tried. It was determined, that ceramic additives in excess of about 5% tended to prevent full densification during sintering. At these levels, the required TCE modification of KU-4 could not be obtained. Next, certain glass viscosity modifiers were considered. One of these imparted the desired characteristics of low dielectric loss, while promoting good densification and higher TCE.

Concurrent with the TCE modification, it was decided to also lower the peak sintering temperature for the complete crystallization of the cordierite from the KU-4 glass. The mere addition of the glass viscosity modifier had been found to lower the peak crystallization temperature in the DTA from 970°C to about 950°C. In other experiments we had noted that adding small amounts of powdered cordierite seed to the green tape, decreased the peak crystallization temperature to 940°C. When both the viscosity modifier and cordierite seed were added to the tape composition, a synergy between their actions, lowered the overall peak crystallization temperature of KU-4 to 925°C. Figure II.2 shows the DTA crystallization peaks of KU-4 by itself, and KU-4 with the glass viscosity modifier, and/or cordierite additions. These efforts finally led to the development of a composite dielectric such as ABT-24, having KU-4 as the principal phase, a glass viscosity modifier, and crystalline cordierite powder as a nucleating agent, which fired flat on Cu/Mo/Cu cores.

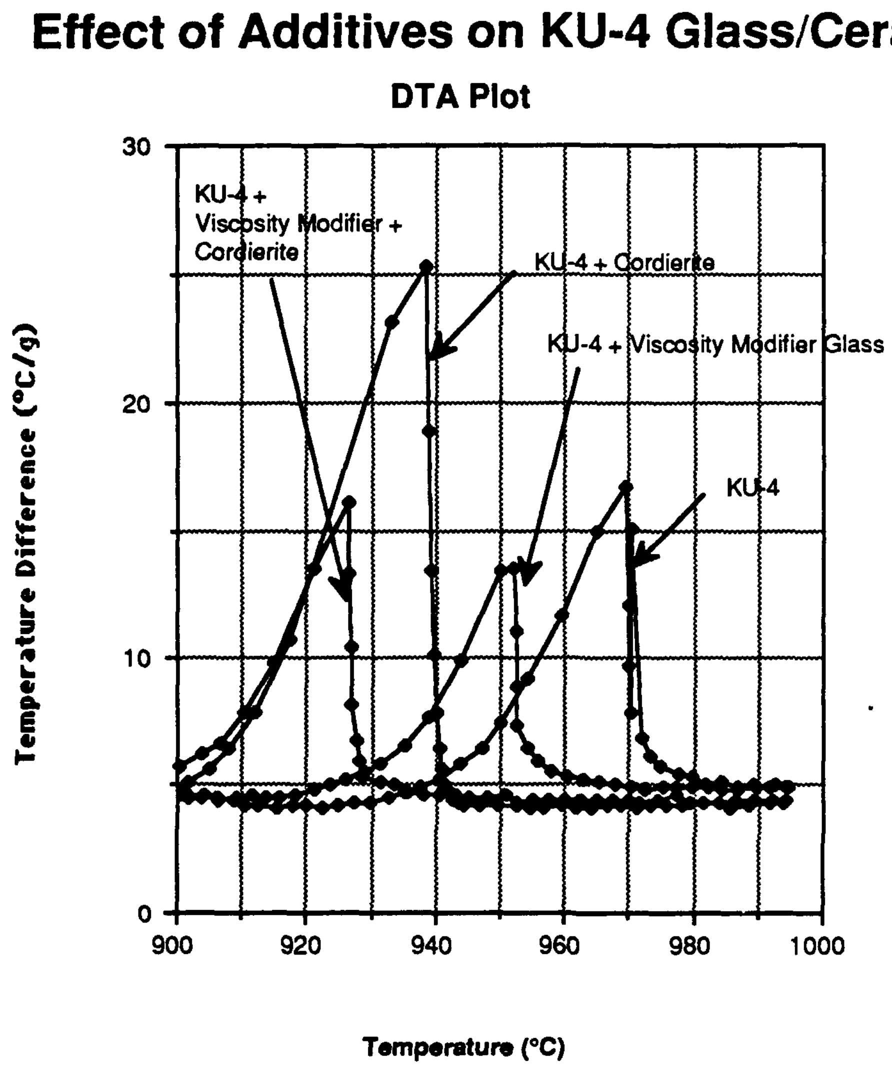


Figure II.2: Effect of additives on the DTA characteristics of the KU-4 glass-ceramic.

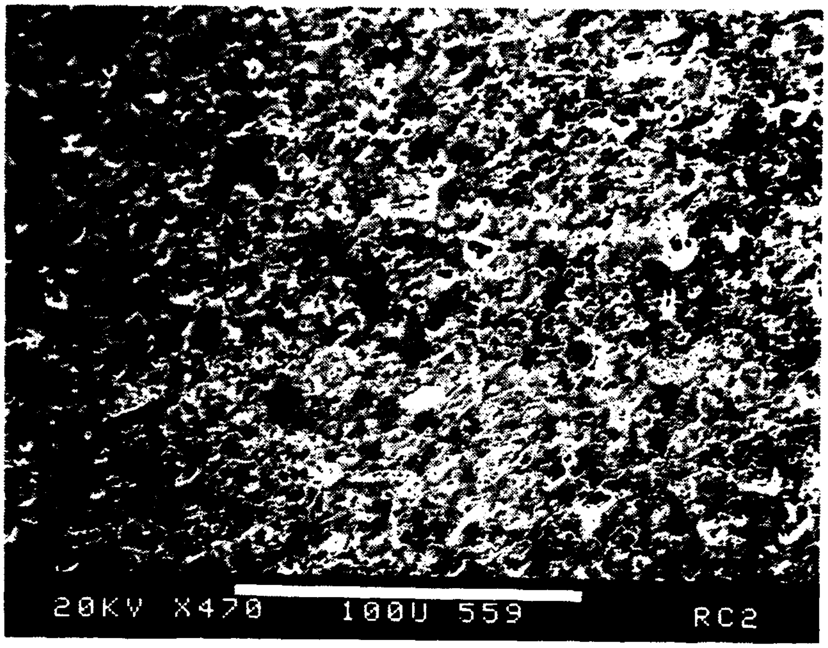


Figure II.3: **Scanning Electron Micrograph of the 2 phase microstructure of ABT-24.**

The ABT-24 dielectric composition has been used to successfully fabricate many LTCC-M structures on Cu/Mo/Cu cores at a peak firing temperature of 850°C, using the methods described later in this report. Some of these substrates contained silver conductors and other structures. In all cases the substrates exhibited little or no camber. The fired dielectric composition has also been found not to be attacked by plating solutions. As shown in Figure II.3 the microstucture of the fired dielectric exhibits a two phase structure with very little porosity.

D. PLAN FOR NEXT QUARTER

During the next quarter the characterization the ABT-24 composition will be completed. This will include the measurement of thermal expansion coefficient and its variation with peak sintering temperature, the dielectric properties at high frequencies, the adhesion of the substrate to the metal core, and the adhesion of silver conductors to its top surface.

Section III
WBS Task 1.3: Cofired Conductors

A. TASK OBJECTIVE

The objective of this task is to develop silver thick film conductor inks capable of producing high density circuits. This will include the development of a buried conductor, a via-fill conductor, and a top conductor. These conductors will subjected to the relevant reliability tests.

B. INTRODUCTION

To fabricate multilayer cofired ceramic interconnect boards, three conductors, having different requirements, must be developed for the ABT-24 green tape. The conductors in the buried layers are required to have high electrical conductivity and fine line printing characteristics. The vias connecting the different layers of the circuit must be hermetic to insure the long term reliability of the circuit. The top layer conductor must solderable, plateable, and have good adhesion to the glass-ceramic.

C. BURIED CONDUCTOR

Buried conductor thick film inks were formulated by mixing silver flake (from Degussa) with a small amount of glass, and an organic vehicle (to obtain the desired rheology for screen printing). It was determined that ABT-24 green tape was compatible with silver thick film ink formulations containing one of several different glasses as well, some containing no glass at all. Since it is expected that the elimination of glass will produce conductors having the highest electrical conductivity, we are presently concentrating on the use of such ink formulations. The measured resistivity of thick film conductors printed and fired as buried conductors in ABT-24 green tape is 4 mΩ/square.

D. VIA CONDUCTOR

Via conductor inks are formulated by mixing silver powder (from Degussa) with glass and an organic vehicle (to obtain the desired rheology for stencil printing). To prevent separation (or cracking) of the silver via from the surrounding glass-ceramic, via formulations generally have a higher glass content than conductor trace inks. A combination of a glasses was found that produces hermetic vias when fired with ABT-24 green tape. This combination includes a low softening point glass and a custom glass, G-63, that crystallizes. Figures III.1 and III.2 show the DTA characteristics of these glasses. Test structures with 8 mil diameter vias show good compatibility between the via formulation and the buried and top conductor inks.

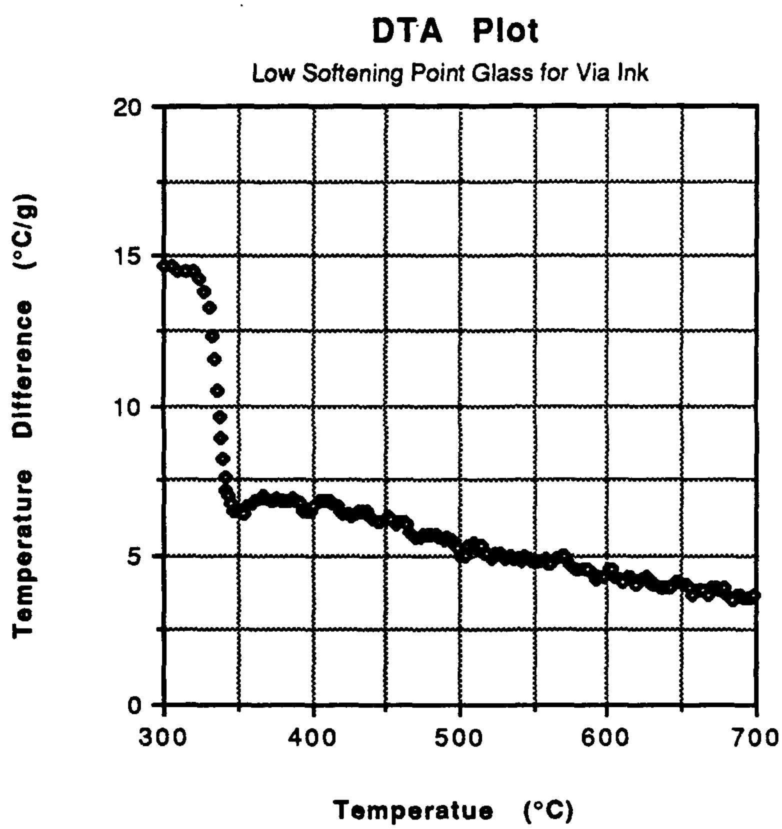


Figure III.1: DTA of the low softening point glass added to the via ink formulation

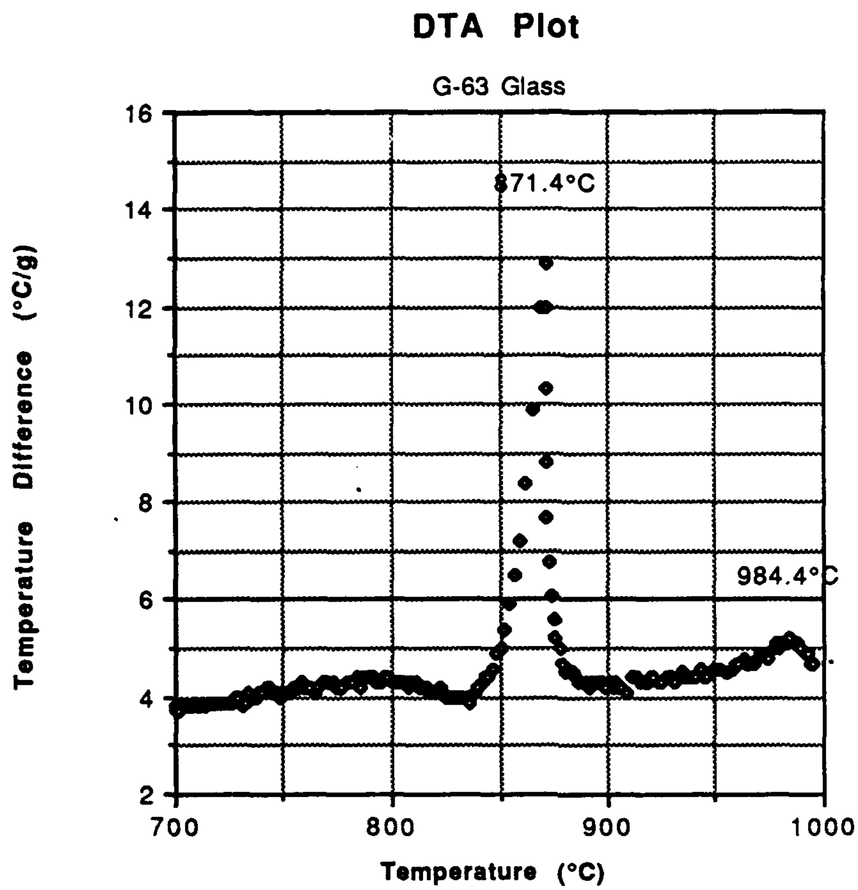


Figure III.2 DTA of the custom glass G-63 added to the via formulation

E. TOP CONDUCTOR

An initial formulation has been developed to test the via test structures. This formulation can be plated by electroless Ni and Au plating baths.

F. PLAN FOR NEXT QUARTER

- Complete development of a top conductor for use with a hermetic enclosure
- Perform thermal cycling testing of test structures

Section IV
WBS Task 1.4: Thin Film Interconnect Structures

A. TASK OBJECTIVE

The objective of this part of the program is to demonstrate that MCM-D interconnect structures can be built on top of the ASEM ceramic substrate. This will be accomplished by the actual fabrication of a multi-level, thin film interconnect structure on the final ASEM test vehicle and subjecting this structure to the relevant reliability tests.

B. PHOTOSENSITIVE BENZO-CYCLO-BUTENE (BCB) DIELECTRIC

Previously we had reported on our evaluations of a photosensitive and a non-photosensitive polyimide, as well as, a non-photosensitive benzo-cyclo-butene (BCB) polymeric dielectric for thin film interconnect fabrication. In this reporting period we carried out evaluation of a photosensitive version of Benzo-cyclo-butene, made by the Dow Chemical Company. The photosensitive versions of polyimide and BCB make processing somewhat simpler because of the dual role played by the dielectric, viz. of being a photoresist as well as a permanent dielectric. The number of major process steps associated with the photosensitive and non-photosensitive versions of polyimide and BCB are compared in Table IV.1. The advantage of photosensitive BCB over photosensitive polyimide lies in the fact that the former does not need a passivating layer of nickel or chromium over the copper features.

Table IV.1: Via Fabrication on Thin Film Metal*

Polyimide	Cyclotene™ BCB
• 22 step process	• 21 step process
• needs barrier layer over Cu	• may be applied directly to Cu
• hygroscopic	• not hygroscopic

Photo Polyimide	Photo BCB
• 18 step process	• 15 step process
• needs barrier layer over Cu	• may be applied directly to Cu
• hygroscopic	• not hygroscopic

* Single conductor layer with unfilled vias

The Dow Chemical Company supplied both the photosensitive BCB materials and the processing expertise for this evaluation. Test structures consisting of vias ranging in diameter from 10µm to 35µm were constructed on both polished alumina and polished ABT-24 glass-ceramic. We were able to open vias of 25µm diameter in a 4 to 5µm thick photosensitive BCB layer. Vias smaller than this were not completely opened. Figure IV.1 shows the test pattern of vias and lines patterned in the photosensitive BCB dielectric.

C. SURFACE FINISH

The characteristic of the substrate that is most relevant to the fabrication of an MCM-D structure on top of is its surface finish. Rough or porous surfaces cause processing difficulties and introduce thin film defects. Hence, it is common practice to polish the substrate surface for thin film interconnect fabrication. We found that the polished surface of the glass-ceramic was non-porous; and as shown in Figure IV.2, it could be polished to the same very high surface finish as 99% alumina.

D. ADHESION OF THIN FILMS TO ABT-24

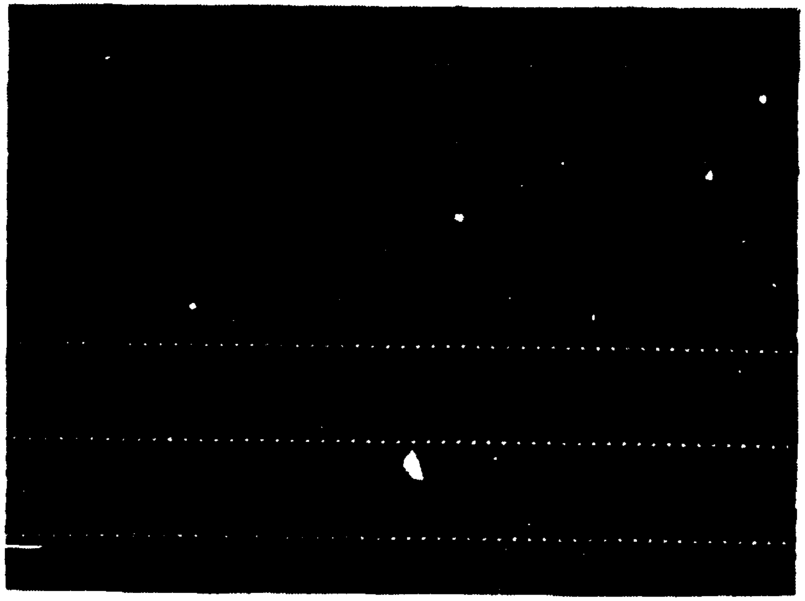
Many applications require thin films directly deposited on top of the LTCC-M ceramic. Initially, the adhesion of plated conductors was achieved by sputtering a thin layer of Cr-Cu on top of the ABT-24 glass ceramic. Qualitative tests indicated that the adhesion was good, but the plated film could be removed by picking at it with a razor blade.

It was determined that the adhesion could be significantly enhanced by the deposition and formation of a Ta_2O_5 film directly on the glass-ceramic, followed by the deposition of a Cr-Cu seed layer for subsequent plating. Plated films deposited by this process showed excellent adhesion to the ABT-24 glass-ceramic.

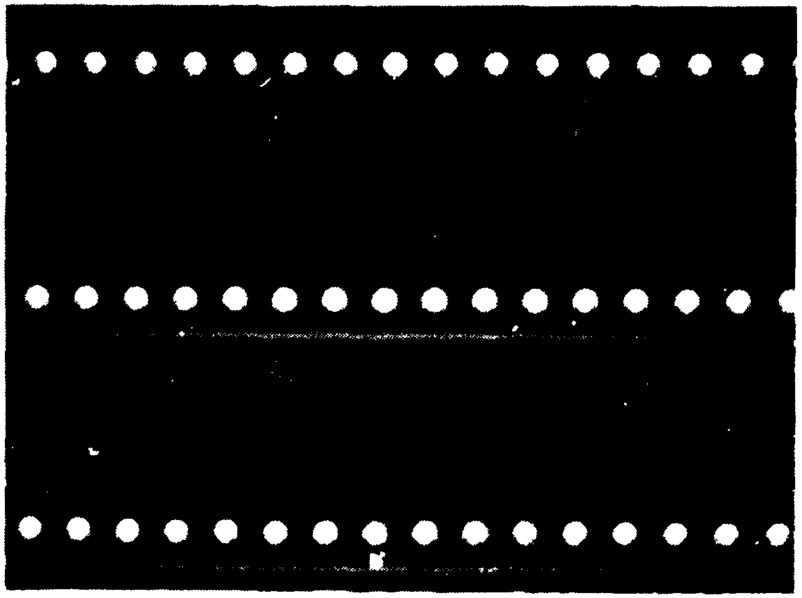
E. PLAN FOR NEXT QUARTER

- Fabricate meander line test pattern for evaluation of microwave properties
- Optimize photosensitive BCB processing to reliably open vias below 25µm in diameter
- Integration of the thin film BCB processing on top of LTCC-M structures

Photo BCB Vias on Defined Metal



- SEM
- 40 x magnification
- 20 and 25μm diameter vias on 75μm wide lines



- SEM
- 100 x magnification
- 25μm diameter vias on 75μm wide lines

Figure IV.1

Polished LTCC

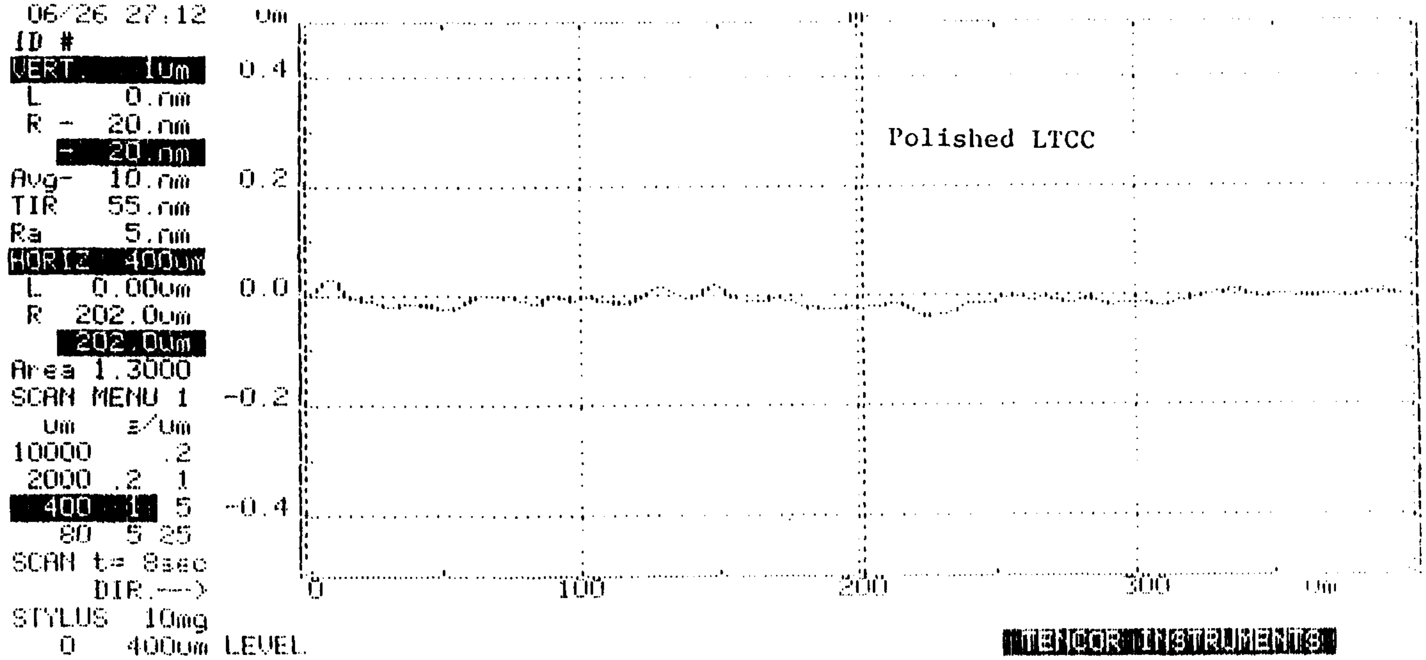
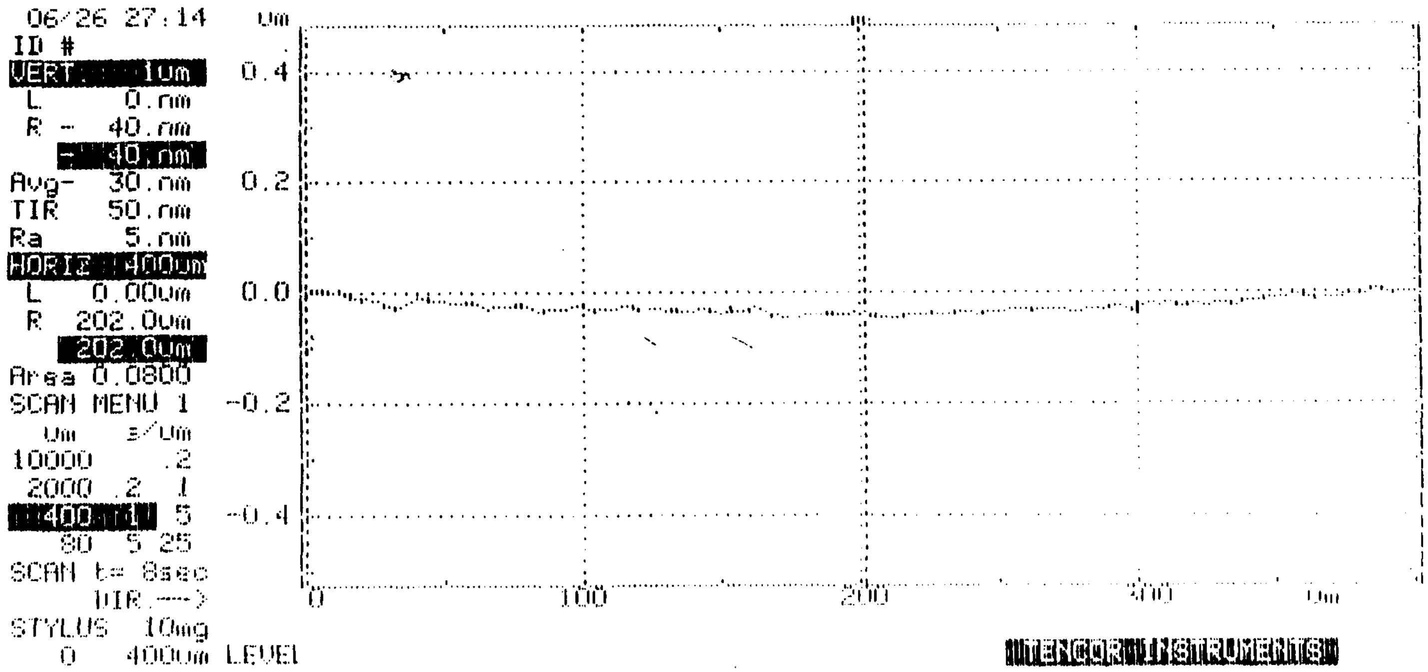


Figure IV.2

Polished 99% A1203



Section V
WBS Task 1.5: Multilayer Integration

A. TASK OBJECTIVE

This task integrates together the metal core with feedthroughs, the green tape, all thick film conductors, and the "zero" shrinkage processing to fabricate double-sided test substrates. This will verify the compatibility of all the processes, which were individually developed in WBS Tasks 1.1 to 1.4. Finally the integrated test structures will be subjected to thermal cycling and high humidity bias and temperature (HHBT) accelerated aging tests.

B. INTRODUCTION

The previous sections described the development of materials and processes for the major components of the double-sided LTCC-M structure. This section will describe their integration, as well as any additional processes needed to produce double-sided modules. The issues involved in fabricating double-sided boards include:

- adapting the lamination to double-sided boards
- burnout of the organic components from the green tape during firing
- optimization of the firing parameters to produce camber free substrates

C. MULTILAYER INTEGRATION RESULTS

The major process steps required to fabricate a double-sided board are shown in Figure V.1. This has resulted in a process that allows both sides of a double-sided board to be simultaneously fired. Presently a bisque fire step, with the double-sided LTCC-M board resting on a fibrous glass mat, is used to remove the organic components prior to final firing step. The LTCC-M circuit is then transferred to a hard surface for the cofiring step, which improves the overall surface finish. Using this process, organics have been readily removed from test structures having as many as 6 layers/side. Test structures (4 layers/side) having vias in the ceramic have been connected together through the electrical feedthroughs in the metal core. These structures have been 100% successful, in that all vias showed electrical continuity and all electrical feedthroughs in the metal core were electrically isolated from the core.

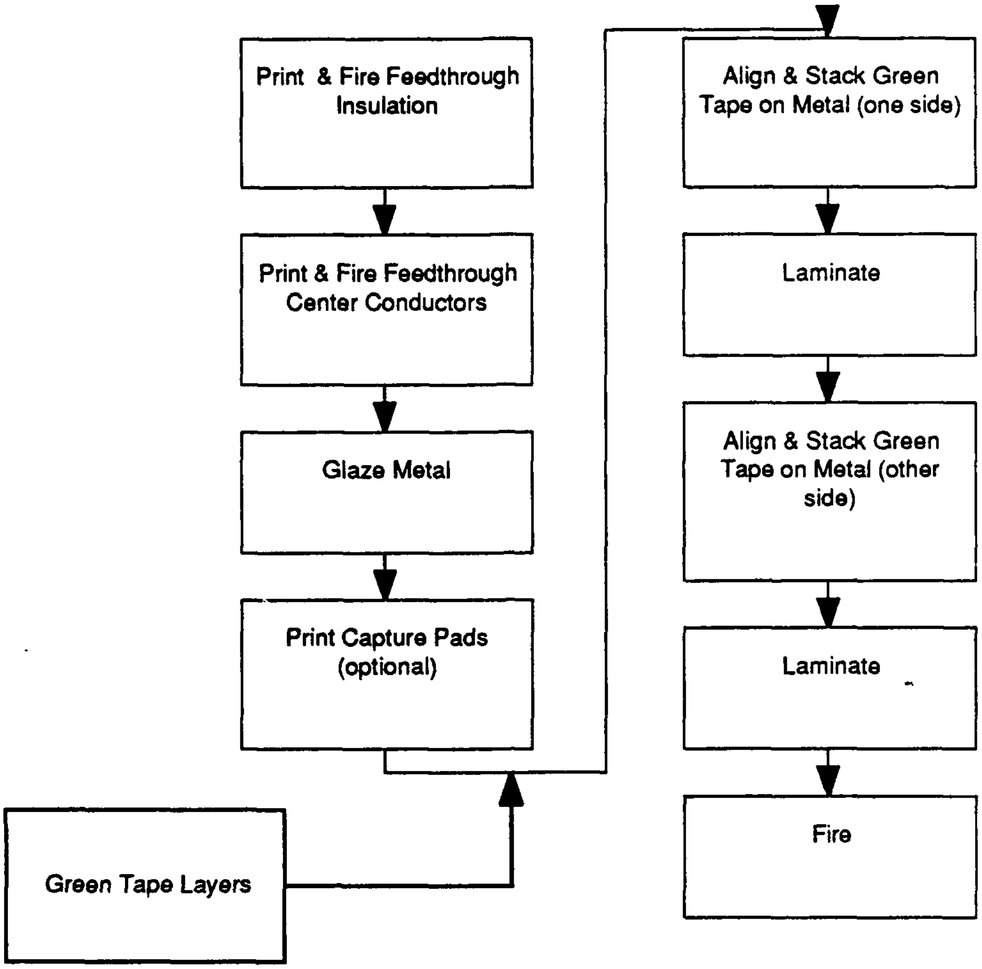


Figure V.1: The major process sequence presently used for producing double-sided LTCC-M boards

D. PLAN FOR NEXT QUARTER

- Produce multilayer test structures having a high density of conductors
- Perform accelerated aging testing on double-sided boards having feedthroughs in the metal core.
- Develop a local hermetic seal

Section VI
Important Findings

A. METAL CORE FABRICATION

- Laser drilling works well
- Lasers can drill smaller and higher aspect ratio holes compared to mechanical drilling
- All processing previously developed for mechanically drilled holes carries over to laser drilled holes
- Feedthroughs are compatible with all subsequent LTCC-M processing
- Laser drilling is the fastest and most cost effective metal core hole formation method
- Successfully demonstrated "zero" x-y shrinkage for the ABT-24 glass-ceramic on Cu/Mo/Cu
- Developed a surface preparation that allowed Cu/Mo/Cu to be processed above 925°C in air without deterioration
- Developed a glaze composition compatible with cordierite forming (KU-4 glass) glass-ceramics and Cu/Mo/Cu
- Defined the bonding glass deposition and reflow parameters

B. LTCC-M CERAMIC DEVELOPMENT

Ceramic/green tape composition for ASEM LTCC-M successfully completed

- Exhibits excellent locking to metal core
- Provides good CTE match to Cu/Mo/Cu core
- Good dielectric characteristics
- Compatible with thick film silver firing
- Yields low porosity glass-ceramic with
- Good surface finish (R_a~0.5μm)
- Resistant to etching by plating solutions

C. COFIRED CONDUCTORS

- Developed a buried Ag conductor, that does not require any glass additions, having a resistivity of 4mΩ/square
- A combination of glasses developed that produce hermetic vias
- An initial candidate top conductor developed that can be plated
- All inks developed are compatible with each other and the metal core feedthroughs

D. THIN FILM INTERCONNECT STRUCTURES

- Thin film metallization process developed for LTCC-M ceramic with excellent adhesion
- Photo BCB provides the most attractive path for thin film multilayer structures on LTCC-M

- Initial development of the Photo BCB process for 25μm via definition on patterned metal is complete

E. MULTILAYER INTEGRATION

- Successfully fabricated double-sided LTCC-M substrates made having 4 layer via stacks on both sides of the Cu/Mo/Cu core connected together by feedthroughs
  - all vias show continuity
  - all vias isolated from one another and the metal core
- Double-sided lamination procedure developed
- Firing sequence developed for complete removal of organics from the double-sided green tape-on-metal stack

Section VII
Significant Developments

The KU-4 glass (principal component of the ABT-24 green tape) has been characterized for insertion loss at frequencies up to 40GHz. Measurement of a test structure having thin film conductors (Cr-Cu covered with a thin layer of Au), showed the same insertion loss as a polished 99.5% Al_2O_3 substrate. This shows that KU-4 glass forms an excellent microwave circuit substrate since the insertion loss was not significantly affected by the ceramic itself. In comparison to traditional thick film hybrids, use of LTCC-M technology is expected to reduce the cost of unpopulated microwave substrates by more than an order of magnitude.

Section VIII
Plan for Further Research

1. Design a high density test pattern for LTCC-M ceramic and thin film BCB interconnect.
2. Fabricate high density test patterns as double-sided LTCC-M substrates with/without BCB overlay.
3. Perform reliability testing on double-sided LTCC-M test structures.
4. Update cost analysis to reflect process revisions.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
9/21/94

3. REPORT TYPE AND DATES COVERED
Technical Report for 6/24/94 to 9/21/94

4. TITLE AND SUBTITLE
Ceramic/Metal Composite Circuit-Board-Level Technology for Application Specific Electronic Modules (ASEMs)

5. FUNDING NUMBERS
DAAB07-94-C-C009

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
David Sarnoff Research Center
CN 5300
Princeton, NJ 08543-5300

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Sponsored by: Advanced Research Project Agcy.
Electronic Systems Tech. Office
Issued by: U.S. Army CECOM
Ft. Monmouth, NJ 07703

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Data Item
DI-MISC-80711

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The quarterly progress for the Ceramic/Metal Composite Circuit-Board-Level Technology for Application Specific Electronic Modules is described in this report. Data is reported for the following tasks: Metal Core Fabrication, LTCC Ceramic Development, Co-fired Conductors, Thin Film Interconnect structure Integration, and Multilayer Integration.

14. SUBJECT TERMS

15. NUMBER OF PAGES
25

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	200 words